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# RESEARCH MEMORANDUM

## STEADY-STATE ENGINE WINDMILLING AND ENGINE SPEED DECAY CHARACTERISTICS OF AN AXIAL-FLOW TURBOJET ENGINE

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
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RESEARCH MEMORANDUM

# STEADY-STATE ENGINE WINDMILLING AND ENGINE SPEED DECAY CHARACTERISTICS OF AN AXIAL-FLOW TURBOJET ENGINE

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## SUMMARY

A brief investigation has been conducted in the NACA Lewis altitude wind tunnel to determine the steady-state engine windmilling characteristics and engine speed decay characteristics of the J34-WE-32 turbojet engine over a range of simulated altitudes from 5000 to 50,000 feet and simulated flight Mach numbers from 0.19 to 1.06. For part of the investigation of the engine speed decay characteristics, an accessory load was used on the engine. The accessory load was approximately constant at 7.8 horsepower for engine speeds above 4000 rpm and decreased with decreasing engine speed. An analysis of the engine speed decay data was made and engine speed decay rates were determined for several hypothetical accessory load conditions.

Corrected steady-state engine windmilling drag and speed without an accessory load are presented as a function of flight Mach number.

The effect of higher altitudes was to increase the time required for the engine speed to decay from the initial speed to the steady-state engine windmilling speed, while the effect of increasing flight Mach number was to decrease the time required.

At an altitude of 5000 feet and a flight Mach number of 0.27, an accessory load of the magnitude used in this investigation had negligible effect on the engine speed decay characteristics. At 40,000 feet, a maximum difference of 500 rpm occurred in the engine speed range near 2000 rpm.

Analysis of the engine speed decay data with hypothetical accessory loads from 0 to 40 horsepower at altitudes of 5000 and 40,000 feet and with a flight Mach number of 0.27 indicated that the engine decelerates more rapidly at 5000 feet altitude than at 40,000 feet when the engine speed is over 3000 rpm. At engine speeds below 2000 rpm the deceleration is more rapid at 40,000 feet. Under steady-state windmilling conditions, greater accessory power may be extracted from the engine at 5000 than at 40,000 feet altitude.

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## INTRODUCTION

As part of an over-all investigation of the performance and operational characteristics of a J34-WE-32 turbojet engine in the NACA Lewis altitude wind tunnel, a brief study was made of the steady-state engine windmilling characteristics and engine speed decay characteristics (the rate of engine speed decay occurring after fuel cut-off).

There is a trend in modern aircraft design to depend increasingly on accessory power for safe flight. In the event of combustion blow-out or other engine failure, the time sufficient power is available for 2296
rapid, sure operation of landing gear, flaps, control power boost, etc., may be critical. Consideration is given herein to the problem of available duration of auxiliary power obtained from engine driven accessories in the event of combustion blow-out or other engine failure. The time, following blow-out, in which the pilot has a chance to restart the engine is also indicated. The steady-state engine windmilling characteristics were obtained only for the condition of no accessory load. The engine speed decay characteristics were obtained with and without an accessory load. Typical windmilling accessory power requirements for a modern fighter type airplane are of the order of 20 horsepower at 4000 rpm and 5 horsepower at 2000 rpm. However, the accessory load available for this investigation was limited to 7.8 horsepower at 4000 rpm, and it decreased to zero at about 1000 rpm. An analysis was therefore made which extends the experimental speed decay data to higher accessory loads.

Data are presented herein to show the effects of altitude from 5000 to 50,000 feet and flight Mach numbers from 0.19 to 1.06 on the steady-state engine windmilling characteristics. Also presented are the effects of altitude from 5000 to 40,000 feet, flight Mach number from 0.27 to 0.7, and, to a limited extent, an accessory load on the engine speed decay characteristics.

## DESCRIPTION OF APPARATUS

The J34-WE-32 turbojet engine (fig. 1) used in this investigation had a static sea-level rating of 3370 pounds thrust at an engine speed of 12,500 rpm and an exhaust gas temperature of 1280° F. Main components of the engine included an eleven-stage axial-flow compressor, an annular direct-flow combustor, two-stage turbine, diffuser, afterburner, variable-area exhaust nozzle, and integrated electronic control.

To simulate an accessory load, a generator was installed on the engine. The generator was loaded by passing the output current through a resistor of approximately 0.141 ohms. Accessory horsepower was then determined from the following equation:

$$\text{Accessory horsepower} = \frac{[\text{Generator voltage}]^2}{(0.141)(746)}$$

The generator voltage regulator maintained approximately constant voltage (and therefore power) at engine speeds above 4000 rpm. At engine speeds below 4000 rpm, the voltage decreased with engine speed. Because the generator was designed for use on an engine of lower rated speed, a continuous operation of the engine at engine speeds above 8000 rpm was not
2296 possible.

The engine was mounted on a wing in the test section of the altitude wind tunnel (fig. 1). Dry refrigerated air was supplied to the engine through a tunnel make-up air system. The air, approximately at sea-level pressure at the entrance of the make-up air system, was throttled to a pressure at the engine inlet corresponding to the desired flight conditions. Engine inlet temperatures correspond to NACA standard altitude conditions except for conditions requiring temperatures below -20° F, which could not be obtained.

To record the transient condition of the engine during an engine speed decay run, oscillograph instruments were used to record engine speed, indicated air speed, and accessory generator voltage. Conventional forms of instrumentation were also used to calibrate the oscillograph data and to determine the steady-state engine windmilling performance (fig. 2).

A list of the symbols and methods of calculations used in this report are presented in appendixes A and B, respectively.

## PROCEDURE

The steady-state engine windmilling data were obtained without the accessory load at altitudes from 5000 to 50,000 feet and over a range of flight Mach numbers from 0.19 to 1.06.

All engine speed decay data were obtained by simulating combustor blow-out by closing a solenoid operated valve in the engine fuel line, when the engine was in steady-state operation. Because of the accessory design limitation, as mentioned earlier, an initial engine speed of approximately 8000 rpm was used for the main portion of the engine speed decay runs. Data were taken at altitudes of 5000, 10,000, and 40,000 feet at several flight Mach numbers, with and without an accessory load. The only data obtained with an initial engine speed of 12,000 rpm were taken at an altitude of 5000 feet and a flight Mach number of 0.27, with and without an accessory load.

Because of the nature of the test equipment used, it was impossible to prevent small variation in engine inlet pressure during an engine speed decay run. However, an investigation of the data indicated that the effect of the variation of engine inlet pressure from the desired value was negligible. Because of the large volume of the wind tunnel, the tunnel static pressure remained approximately constant during an engine speed decay run.

## RESULTS AND DISCUSSION

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### Steady-State Engine Windmilling Characteristics

The corrected steady-state engine windmilling drag and speed, without an accessory load, are presented as functions of flight Mach number in figures 3 and 4, respectively. Changes in altitude did not affect corrected steady-state engine windmilling drag up to a flight Mach number of approximately 0.5; however, for flight Mach numbers above 0.5, the corrected steady-state engine windmilling drag decreased slightly as the altitude was increased above 25,000 feet. The corrected steady-state engine windmilling drag at altitudes up to 25,000 feet varied from 0.6 percent of the rated static sea-level engine thrust at a flight Mach number of 0.2 to 25.8 percent at a flight Mach number of 0.95. The variation of corrected steady-state engine windmilling speed with flight Mach number (fig. 4) was sufficiently small that data for altitudes from 5000 to 25,000 feet could be represented by a single curve. Above 25,000 feet, the corrected steady-state engine windmilling speed decreased as the altitude was increased. For altitudes up to 25,000 feet, the corrected steady-state engine windmilling speeds for flight Mach numbers of 0.2 and 0.95 were 1150 and 6950 rpm, respectively.

### Engine Speed Decay

Typical oscillograph traces for an engine speed decay run with an accessory load are shown in figure 5. The extent of the indicated air speed variations is typical of all the runs which were made from an initial engine speed of approximately 8000 rpm.

Data from similar oscillograph traces were transferred into a more convenient form and have been combined to show the effects of altitude, flight Mach number, and accessory load on engine speed decay in figures 6, 7, and 8, respectively.

Effect of altitude. - The rate of engine speed decay is dependent on: (1) the inertia of the rotating elements, (2) ram energy of the incoming air into the engine inlet, (3) mechanical friction of the rotating parts, and (4) internal aerodynamic friction of the engine.

As altitude is increased, the inertia and mechanical friction of the rotating parts remain essentially constant, while the magnitudes of the ram energy of the incoming air and the internal aerodynamic friction of the engine decrease. The effect on the rate of engine speed decay, of increasing altitude at a flight Mach number of 0.27 is shown in figure 6. The time required for engine speed to decay from approximately 8000 rpm to 2000 rpm increased from 16 seconds at 5000 feet to 43 seconds at 40,000 feet. Therefore it is evident that the difference between the internal aerodynamic friction of the engine and the energy of the ram air is greater at low than at high altitude. Extrapolation of the speed decay curves to an initial speed of 12,000 rpm indicates that deceleration from 12,000 to 8000 rpm would occur in approximately 2 seconds at an altitude of 5000 feet and in about 4 to 6 seconds at an altitude of 40,000 feet. Thus the speed decay time from 12,000 to 2000 rpm would be increased from 18 seconds at 5000 feet to about 48 seconds at 40,000 feet.

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<u>Effect of flight Mach number.</u> - From figure 7, it is seen that speed decay rates between engine speeds of 8000 and 6000 rpm were not appreciably affected by flight Mach number at any altitude within the range investigated. The probable reason is that at high engine speeds the rotor inertia is high as compared to the friction losses and ram energy of the inlet air stream. At engine speeds below 6000 rpm, the rate of speed decay decreased with an increase in flight Mach number. However, because the difference between the initial engine speed and steady-state engine windmilling speed decreased with increasing flight Mach number, the effect of increasing flight Mach number was to decrease the time required for the engine speed to decay from the initial speed to the steady-state engine windmilling speed. At 10,000 feet the time required for the engine speed to decay from the initial speed to the steady-state windmilling speed was decreased from 48 to 19 seconds by increasing flight Mach number from 0.27 to 0.7. At 40,000 feet, the time decreased from 84 to 58 seconds when flight Mach number was increased from 0.27 to 0.53.

<u>Effect of accessory load.</u> - The expected effect of adding an accessory load to an engine is to increase the speed decay rate. However, in this investigation, the magnitude of the accessory load was small (7.8 hp for engine speeds above 4000 rpm and decreasing with speed at lower speeds) as compared to the other forces acting on the engine during a speed decay, particularly at the higher speeds. Consequently, at 5000 feet altitude, the load and no-load speed decay curves shown in figure 8 are coincident, while at 40,000 feet the maximum difference between the two conditions was about 500 rpm, and this occurred in the range of engine speeds near 2000 rpm. The accessory load at 40,000 feet altitude had decreased to approximately one horsepower at an engine speed of 2000 rpm. If loads of the order of one or two horsepower had been maintained at speeds lower than 2000 rpm, it is possible that the decay curves would have been affected considerably in this speed range.

## Analysis of Engine Speed Decay Data

Because of the previously mentioned limitations of the power extraction device, the effect of larger or more representative accessory loads on engine speed decay characteristics (particularly near the steady-state windmilling speed) were not defined. Consequently, an analysis was made and speed decay rates were determined for several hypothetical load conditions. Experimental data were used to determine slopes of decay curves and were applied in the analysis. No attempt was made to extend this analysis for engine speeds below the steady-state engine windmilling speed obtained with no accessory load, because experimental data showing the effect of accessory load on steady-state engine windmilling speed were not obtained. A more complete description of the analysis is given in appendix B.

The results of the analysis, in which constant hypothetical accessory loads of 5, 10, 20, and 40 horsepower were imposed on the engine during an engine speed decay, are presented in figure 9. For engine speeds over 3000 rpm, the slopes of the speed decay curves, with any given accessory load, are greater at 5000 than at 40,000 feet altitude. As speed decreases below 2000 rpm the slopes of the curves for 40,000 feet become steeper than those for 5000 feet. Extrapolation indicates that accessory loads of the order of 5 horsepower might stop the engine at 40,000 feet altitude while it may be possible to attain steady-state windmilling with loads as high as 10 horsepower at 5000 feet altitude.

Since rotor inertia and mechanical friction are independent of altitude, the differences between the constant accessory load curves for 5000 and 40,000 feet in figure 9 must be due to the relative values of internal aerodynamic drag and the energy of the ram air (see section entitled "Effect of altitude"). Ram energy is independent of engine speed, but aerodynamic drag increases with engine speed. Consequently, at high engine speeds, the aerodynamic drag is considerably larger than the ram energy. Then, since both ram energy and aerodynamic drag are decreased when altitude is increased and since the aerodynamic drag is larger than the ram energy, the engine decelerates more rapidly at low than at high altitude. As engine speed is decreased, however, the aerodynamic drag becomes less than the ram energy with the result that more power may be extracted from the engine at low altitude than at high without stopping the engine.

## SUMMARY OF RESULTS

1. The corrected steady-state engine windmilling drag, without an accessory load and at altitudes up to 25,000 feet, varied from 0.6 percent of the rated static sea-level engine thrust at a flight Mach number of 0.2 to 25.8 percent at a flight Mach number of 0.95. The corresponding variation in corrected steady-state engine windmilling speed was from 1150 to 6950 rpm.

2. At altitudes of 5000 and 40,000 feet and without an accessory load, the time required for the engine speed to decay from the initial speed of 8000 rpm to 2000 rpm was 16 and 43 seconds, respectively. At an altitude of 10,000 feet, increasing flight Mach number from 0.27 to 0.7 decreased the time required for the engine speed to decay from the initial speed of 8000 rpm to the steady-state engine windmilling speed from 48 to 19 seconds. At an altitude of 40,000 feet, increasing flight Mach numbers from 0.27 to 0.53 reduced the speed decay time from 84 to
2296 58 seconds.

3. At an altitude of 5000 feet, the engine speed decay rates with and without an accessory load were equal, while at 40,000 feet a maximum difference of 500 rpm occurred between the two conditions in the engine speed range near 2000 rpm.

4. Analysis of the data at a flight Mach number of 0.27 and for the engine speed decay range between 8000 rpm and no-load steady-state engine windmilling speed indicates that with any given accessory load and with engine speeds over 3000 rpm the engine decelerates more rapidly at 5000 feet than at 40,000 feet altitude. With engine speeds below 2000 rpm the deceleration is more rapid at 40,000 feet. It is possible that a 5-horsepower load would completely stop the rotor at 40,000 feet, but at 5000 feet a steady-state windmilling condition might be achieved with a load as high as 10 horsepower.

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National Advisory Committee for Aeronautics
Cleveland, Ohio

# APPENDIX A

## SYMBOLS

The following symbols are used in this report:

| | |
|---|---|
| $D_w$ | engine windmilling drag, lb |
| $g$ | acceleration due to gravity, 32.2 ft/sec$^2$ |
| $I$ | moment of inertia, lb-ft-sec$^2$ |
| $M_0$ | flight Mach number |
| $N$ | engine speed, rpm |
| $P$ | total pressure, lb/sq ft absolute |
| $p$ | static pressure, lb/sq ft absolute |
| $Q$ | torque, lb-ft |
| $R$ | gas constant, 53.3 ft-lb/(lb)($^{\circ}$R) |
| $T$ | total temperature, $^{\circ}$R |
| $t_e$ | equivalent ambient static temperature, $^{\circ}$R |
| $V$ | velocity, ft/sec |
| $w_a$ | air flow, lb/sec |
| $\alpha$ | angular deceleration, radians/sec$^2$ |
| $\gamma$ | ratio of specific heats |
| $\Delta$ | small increment |
| $\delta_0$ | ratio of absolute tunnel static pressure, $p_0$, to absolute static pressure of NACA standard atmosphere at sea level |
| $\theta_0$ | ratio of absolute equivalent ambient static temperature, $t_e$, to absolute static temperature of NACA standard atmosphere at sea level |

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Subscripts:

| | |
|---|---|
| 0 | free-air stream |
| 1 | engine inlet |
| 7 | exhaust-nozzle inlet |
| j | jet |

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## APPENDIX B

## METHOD OF CALCULATIONS

Flight Mach number. - In calculating flight Mach number, complete ram pressure recovery at the engine inlet was assumed and the following formula was used:

$$M_0 = \sqrt{\frac{2}{\gamma_1 - 1}\left[\left(\frac{P_1}{p_0}\right)^{\frac{\gamma_1 - 1}{\gamma_1}} - 1\right]}$$

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Equivalent ambient-air temperature. - Equivalent ambient-air temperature was determined from the following expression:

$$t_e = T_1\left(\frac{p_0}{P_1}\right)^{\frac{\gamma - 1}{\gamma}}$$

Steady-state engine windmilling drag. - The engine windmilling drag was calculated by the following equations:

$$D_w = \frac{w_a}{g}\left(V_0 - V_j\right)$$

where

$$V_j = \sqrt{\frac{2\gamma_7}{\gamma_7 - 1}\, g\, RT_7\left[1 - \left(\frac{p_0}{P_7}\right)^{\frac{\gamma_7 - 1}{\gamma_7}}\right]}$$

and

$$V_0 = \sqrt{\frac{2\gamma_1}{\gamma_1 - 1}\, gRT_1\left[1 - \left(\frac{p_0}{P_1}\right)^{\frac{\gamma_1 - 1}{\gamma_1}}\right]}$$

During an engine speed decay, the aerodynamic and mechanical friction forces tend to decelerate the engine, while the force due to the ram energy of the incoming air tends to accelerate the engine. These forces are reflected in the engine as torques. During an engine speed decay, the resultant value of the torque produces a deceleration in the engine speed; that is, the torque due to the aerodynamic and mechanical friction forces is greater than the torque due to the ram energy of the incoming air. When the engine is windmilling in a steady-state condition, the resultant torque is equal to zero.

From conservation of angular momentum, which may be expressed

$$Q = I\alpha \tag{1}$$

it is possible to determine the value of the resultant torque acting on
2296 the engine during a speed decay with no accessory load. The angular deceleration $\alpha$ for any engine speed can be determined from the experimentally determined curve of engine speed versus time by use of the following equation

$$\alpha = \frac{\Delta N}{\Delta t} \tag{2}$$

With $\alpha$ and $I$ known, and by use of equation (1), a curve of resultant torque versus engine speed may be plotted. The resultant torque was computed from the engine speed decay data for altitudes of 5000 and 40,000 feet and flight Mach number 0.27.

To determine the value of angular deceleration with an accessory load, the following equation is used:

$$Q_L + Q_e = I\alpha \tag{3}$$

where $Q_L$ is the torque due to the constant hypothetical accessory load and $Q_e$ is the resultant torque due to the forces acting on the engine during an engine speed decay with no load.

From equation (3) a curve of engine speed versus angular deceleration may be drawn. Again from equation (2), a speed decay curve of engine speed versus time may be determined for a constant hypothetical accessory load.

The method of analysis presented is valid only for engine speeds above that obtained at steady-state windmilling conditions with no accessory load. Because no experimental data were obtained to show the effect of accessory load on steady-state engine windmilling speed, the analysis could not be extended to engine speeds below that obtained at steady-state windmilling conditions with no accessory load.

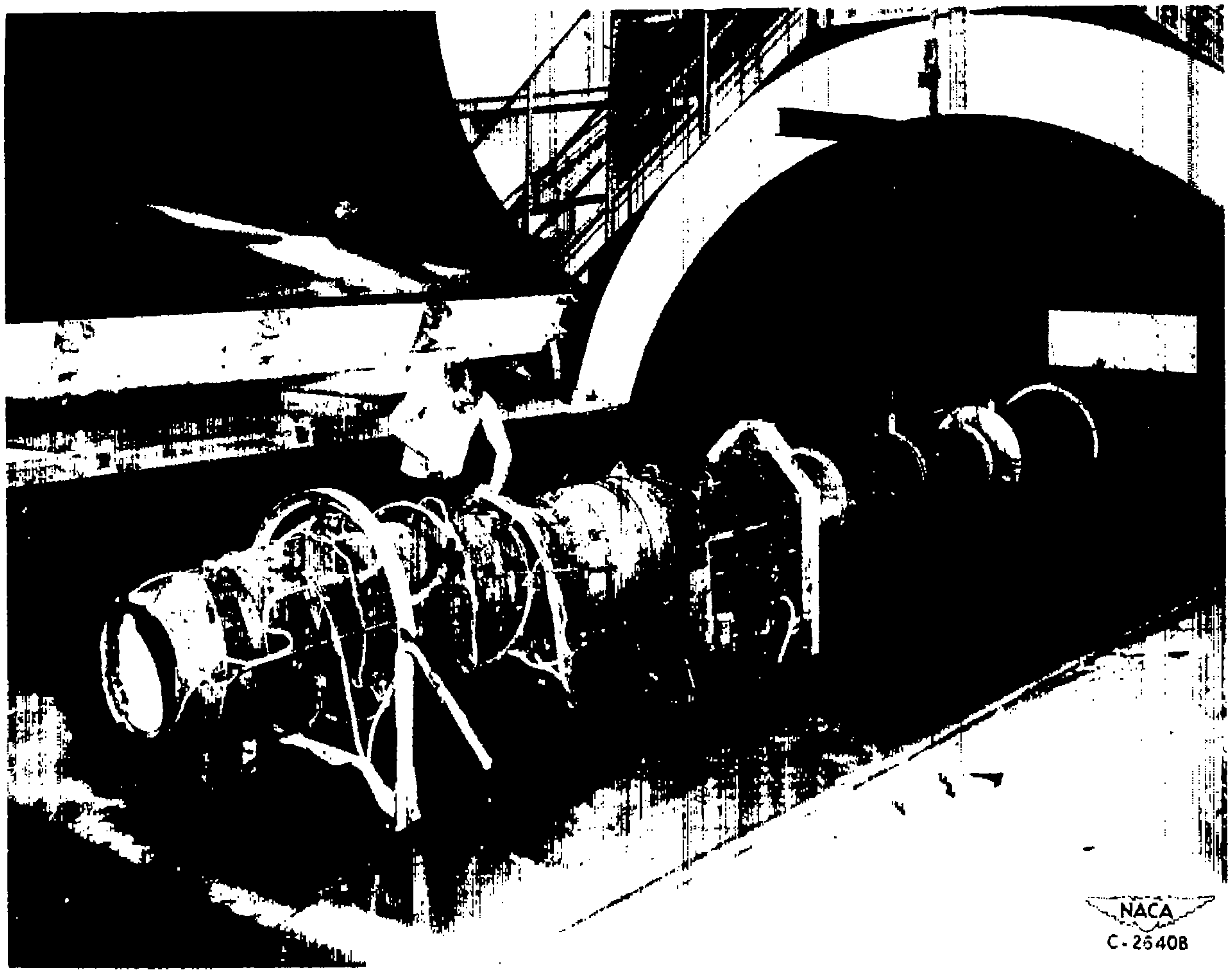


Figure 1. - The J34-WE-32 turbojet engine installed in test section of altitude wind tunnel.

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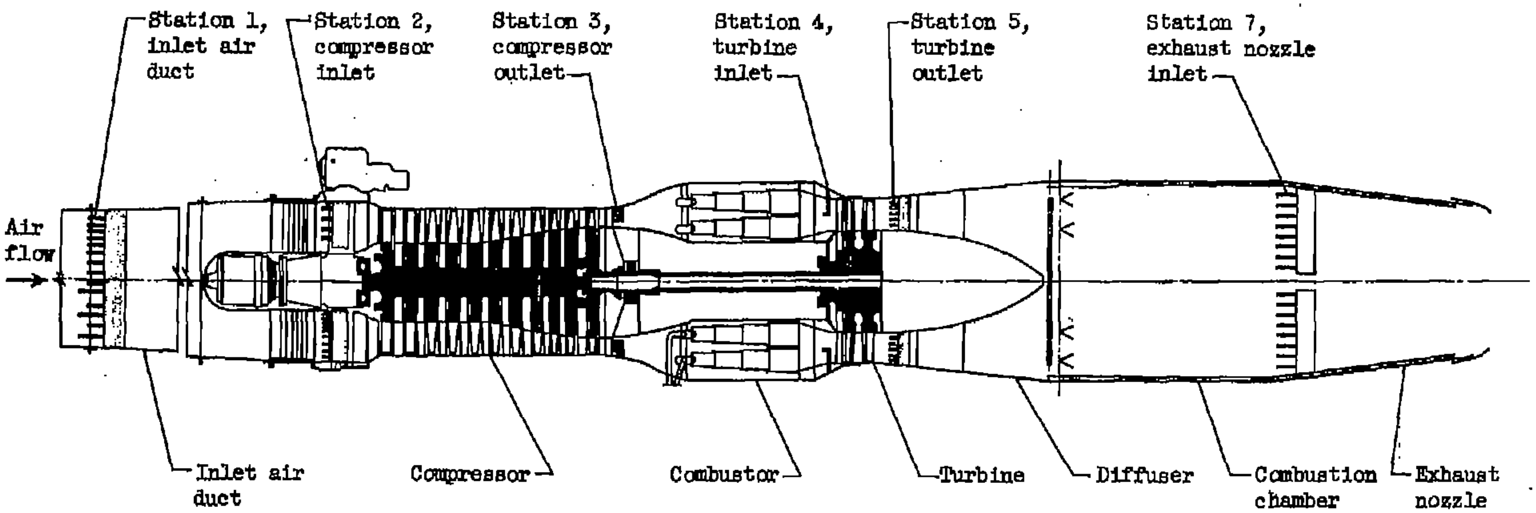


Figure 2. - Cross section of engine showing location of instrumentation.

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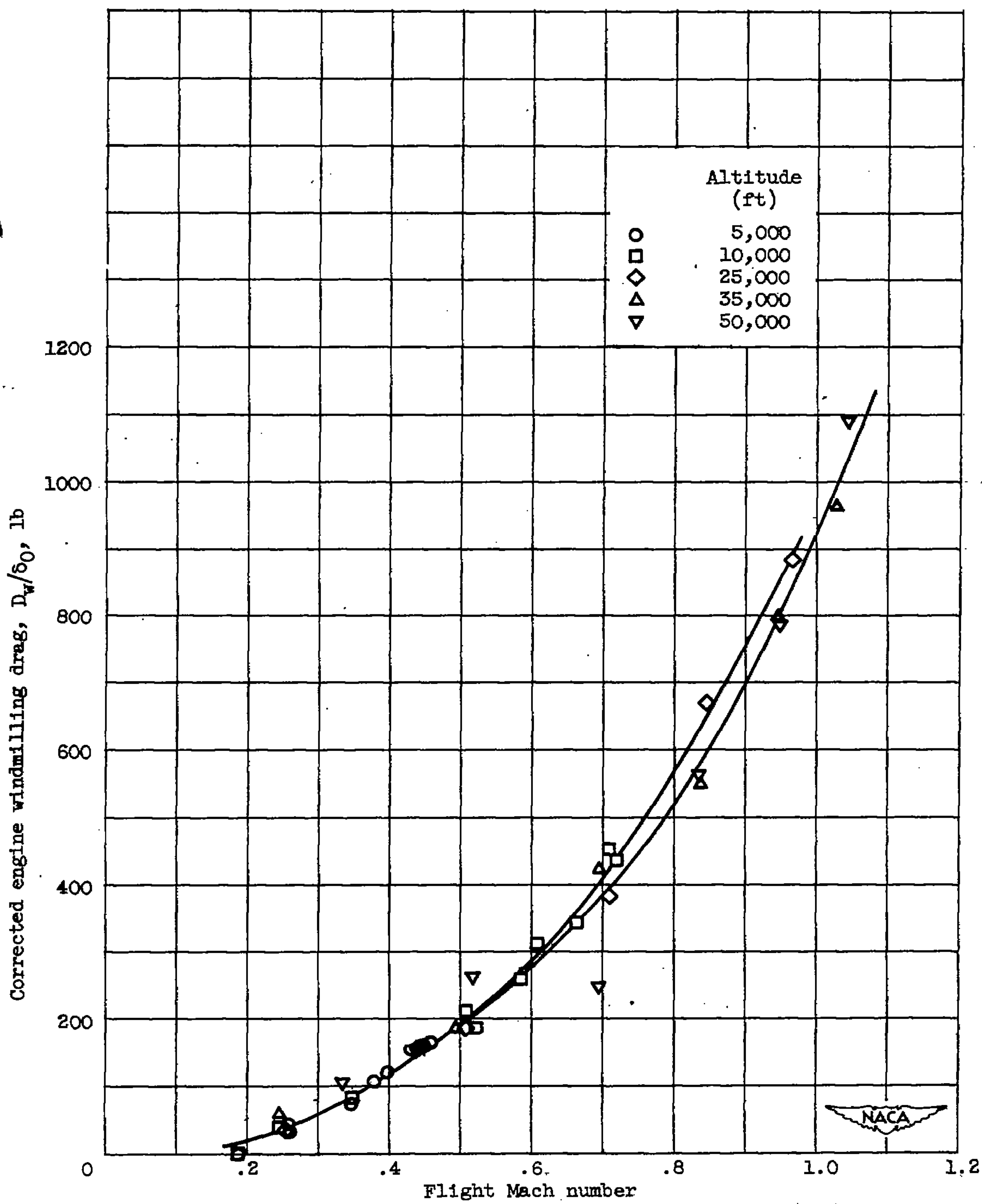


Figure 3. - Variation of steady-state engine windmilling drag with flight Mach number. Altitude, 5000 to 50,000 feet; no accessory load.

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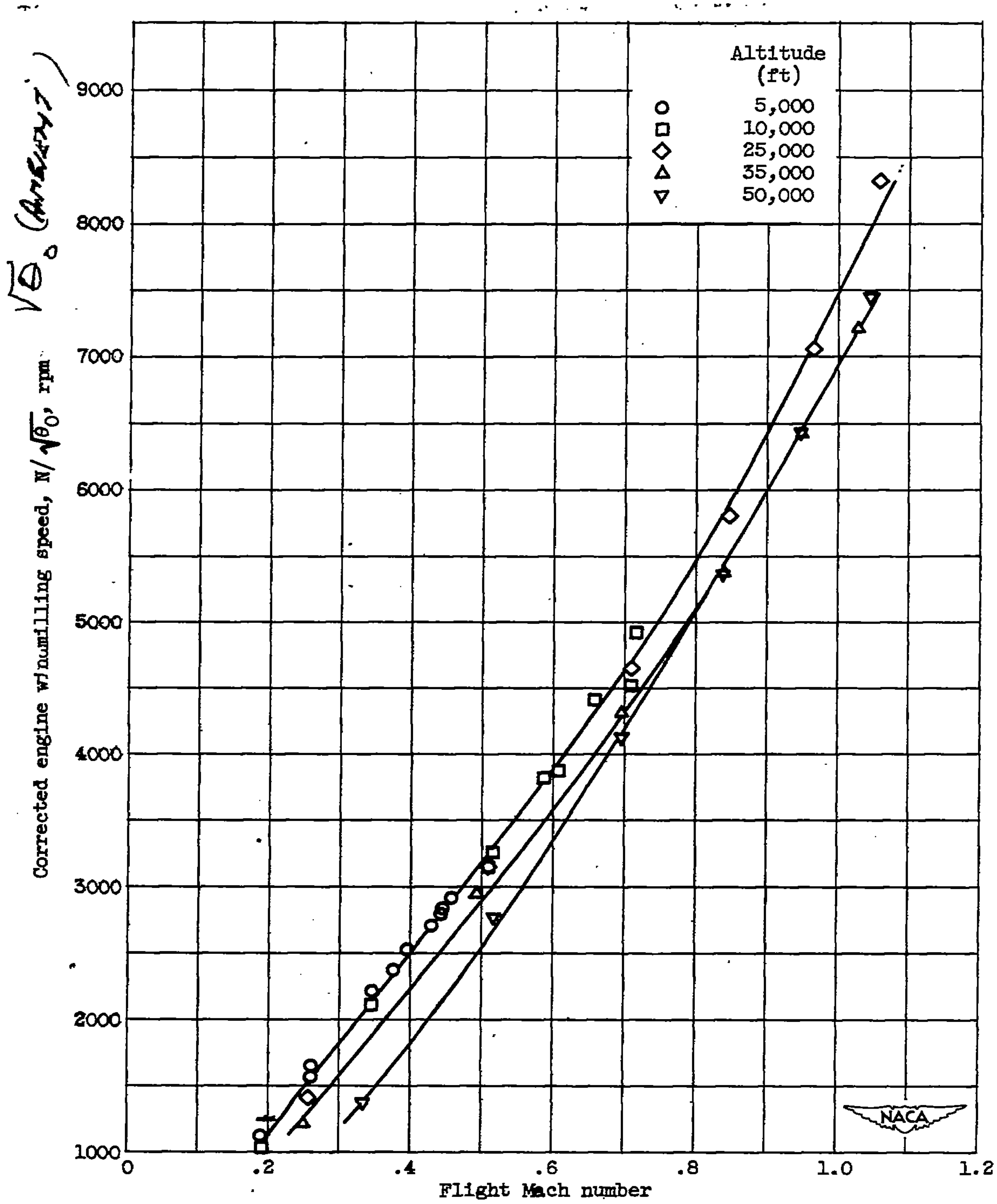


Figure 4. - Variation of steady-state engine windmilling speed with flight Mach number. Altitude, 5000 to 50,000 feet; no accessory load.

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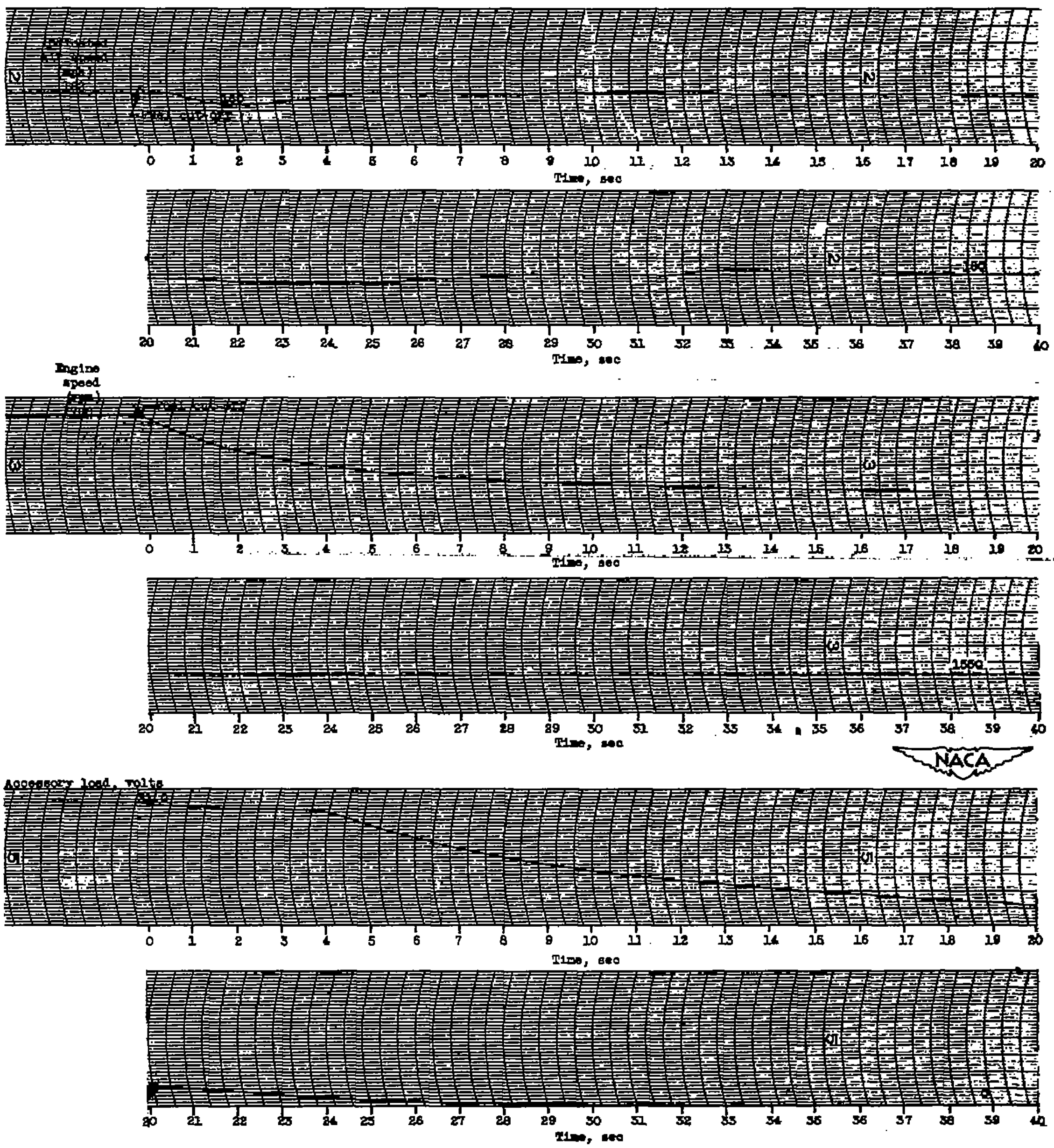



Figure 5. - Typical oscillograph traces showing variation of indicated air speed, engine speed, and accessory load voltage after fuel cut-off. Initial engine speed, 7700 rpm; altitude, 5000 feet; nominal flight Mach number, 0.27.

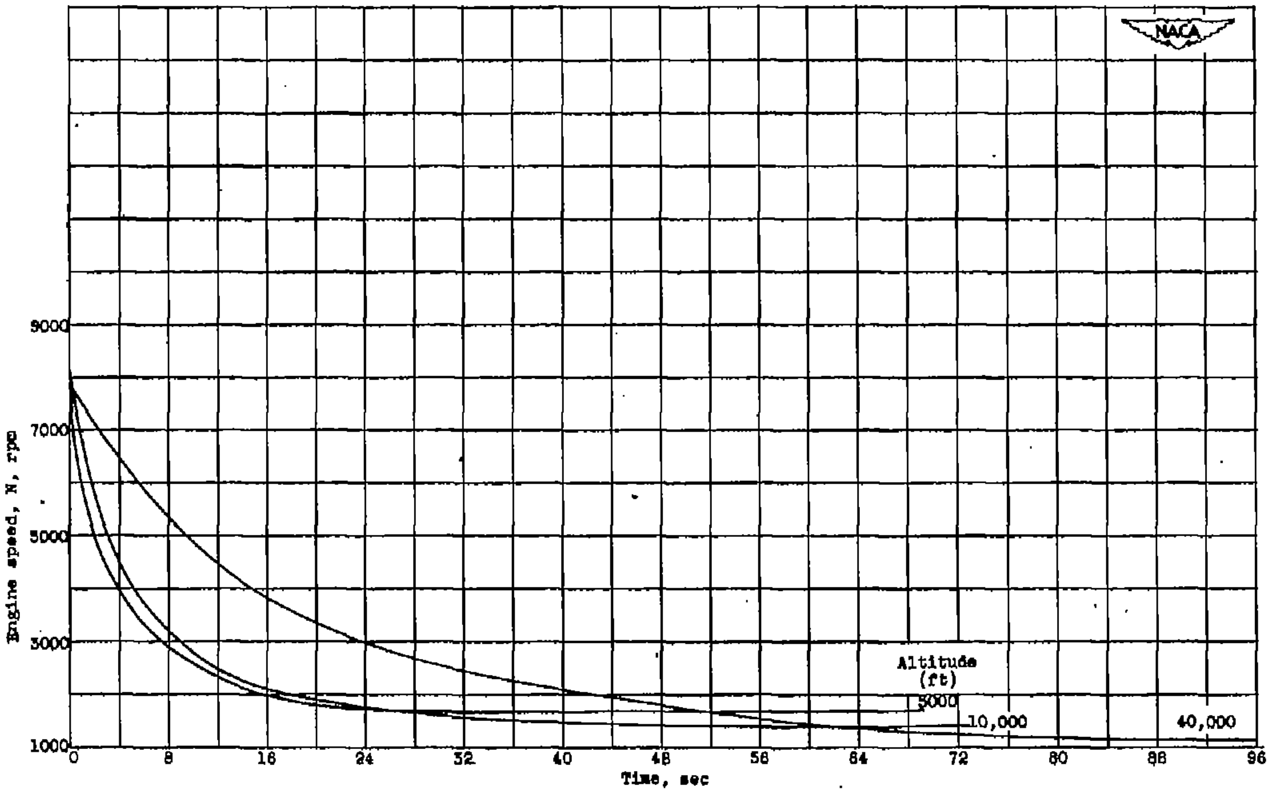
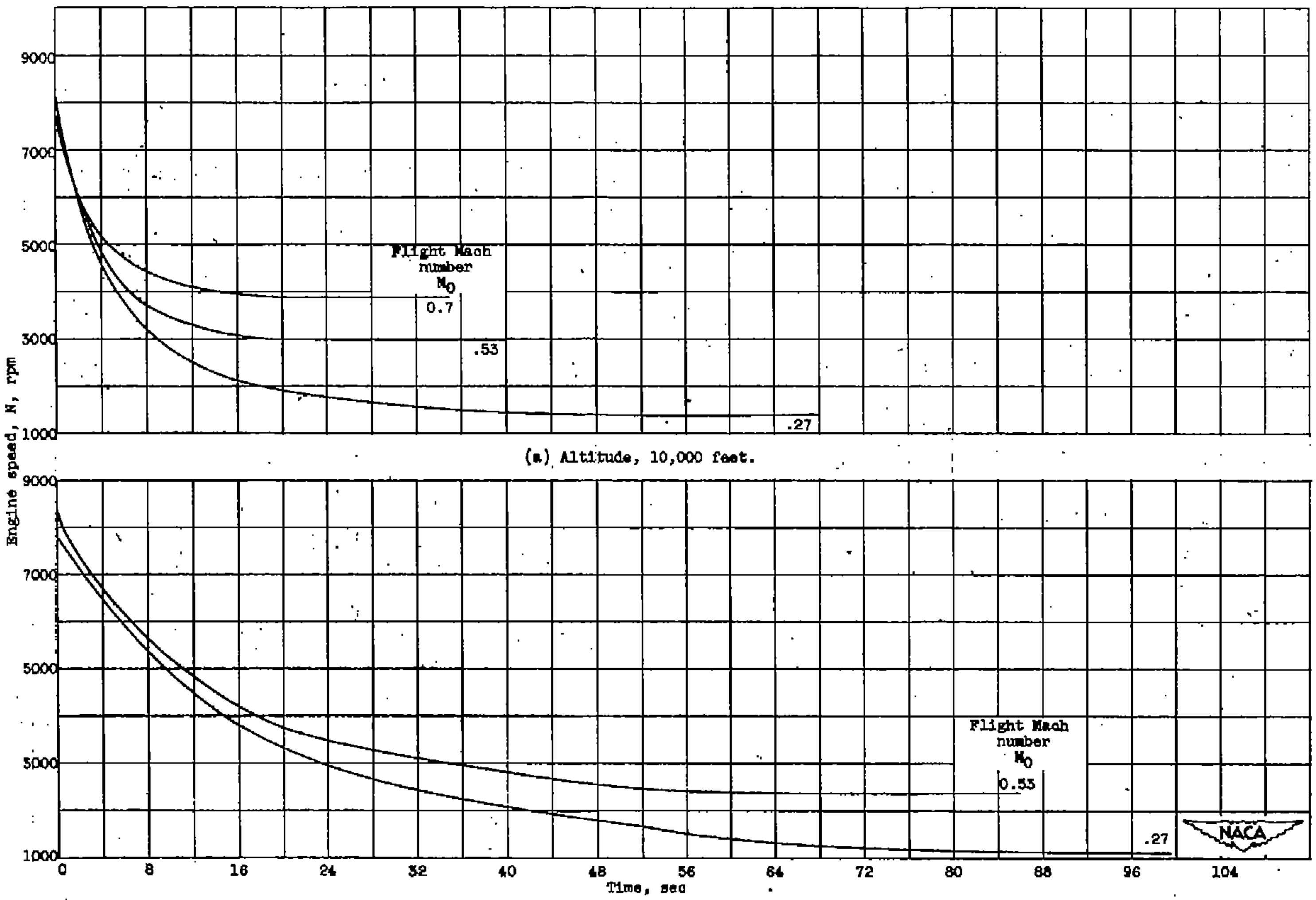
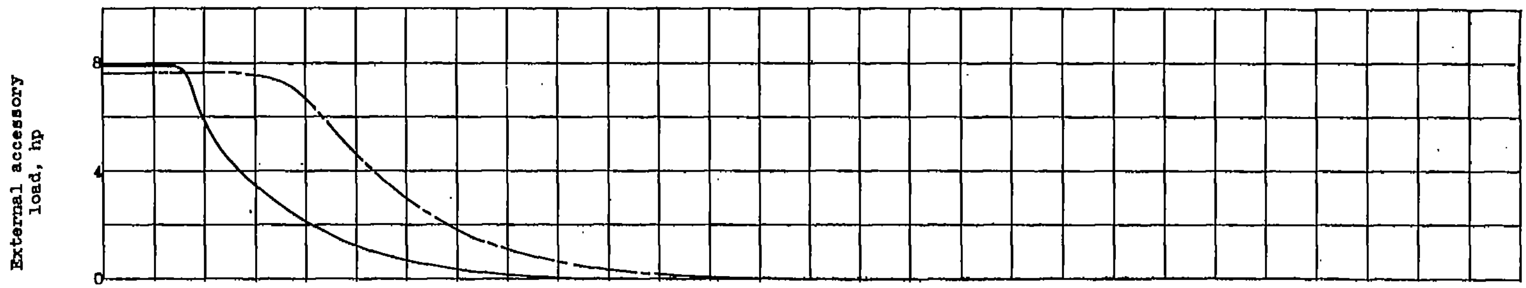



Figure 6. - Effect of altitude on engine speed decay rate following fuel cut-off. Flight Mach number, 0.27; no accessory load.

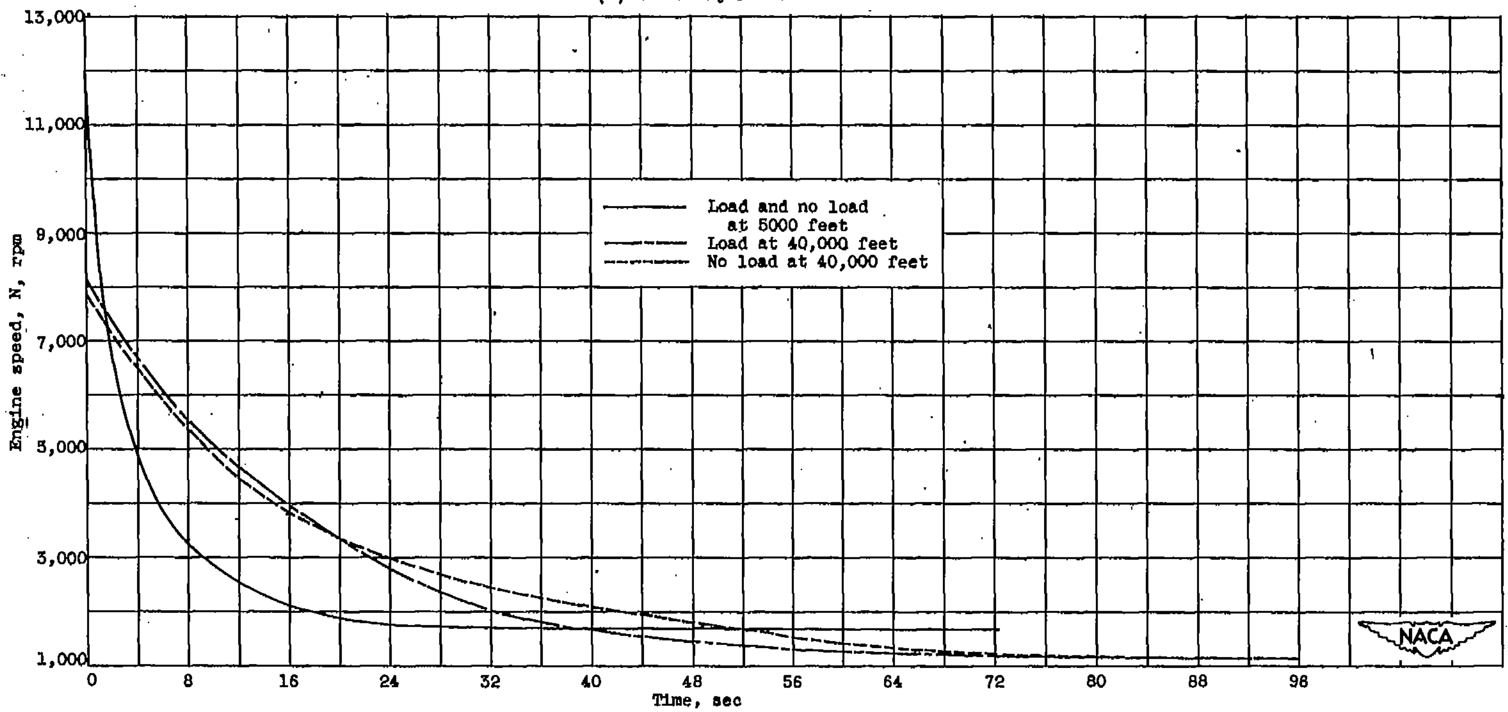



(b) Altitude, 40,000 feet.

Figure 7. - Effect of flight Mach number on engine speed decay rate following fuel cut-off. Altitude, 10,000 and 40,000 feet; no accessory load.




(a) Accessory load.




(b) Engine speed.

Figure 8. - Variation of accessory load and engine speed with time following fuel cut-off. Altitude, 5000 and 40,000 feet; flight Mach number, 0.27.

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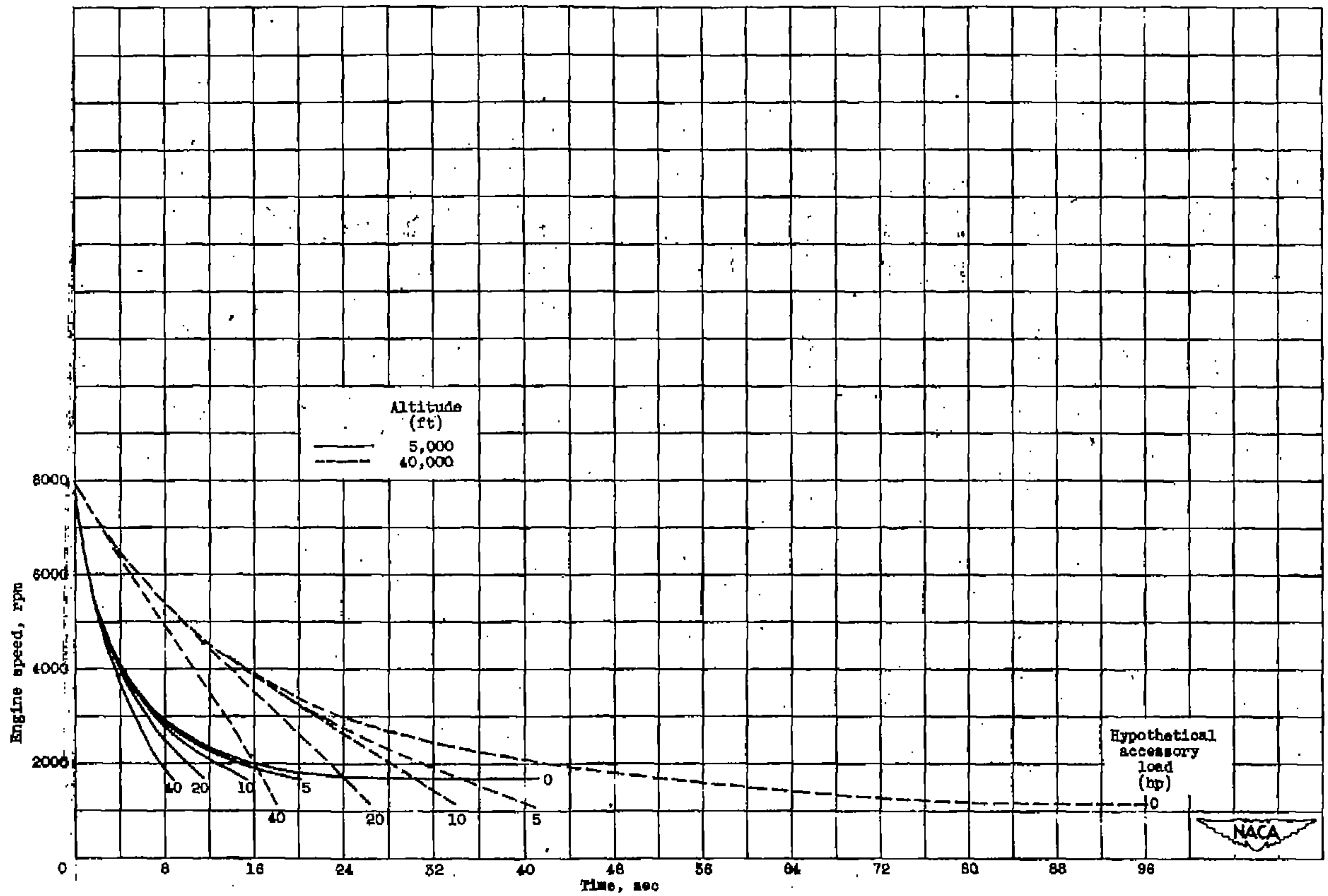


Figure 9. - Effect of constant hypothetical accessory load on engine speed decay rate following fuel cut-off. Altitude, 5000 and 40,000 feet; flight Mach number, 0.27.

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